Testing the Neutrino mass ordering with JUNO detector via Atmospheric and reactor neutrino

Mariam Rifai
Under the supervision of João Pedro Athayde Marcondes De André
and co-supervision of Leonidas N. Kalousis
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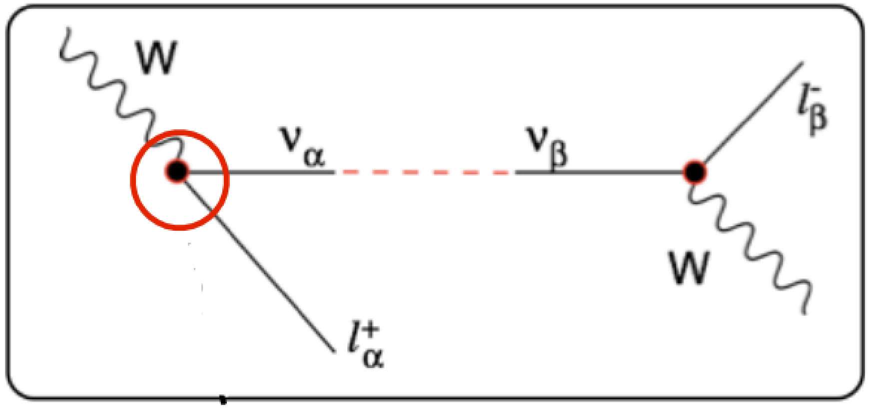
Neutrino Oscillation

- Discovery of Neutrino oscillation (atmospheric and solar neutrinos experiments) leads to a non-zero neutrino mass
- The flavors eigenstates describes as mixtures of mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & & \\ & c23 & s23 \\ & -s23 & c23 \end{pmatrix} \begin{pmatrix} c13 & & s13e^{-i\delta} \\ & 1 & \\ -s13e^{-i\delta} & & c13 \end{pmatrix} \begin{pmatrix} c12 & s12 & \\ -s12 & c12 & \\ & & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

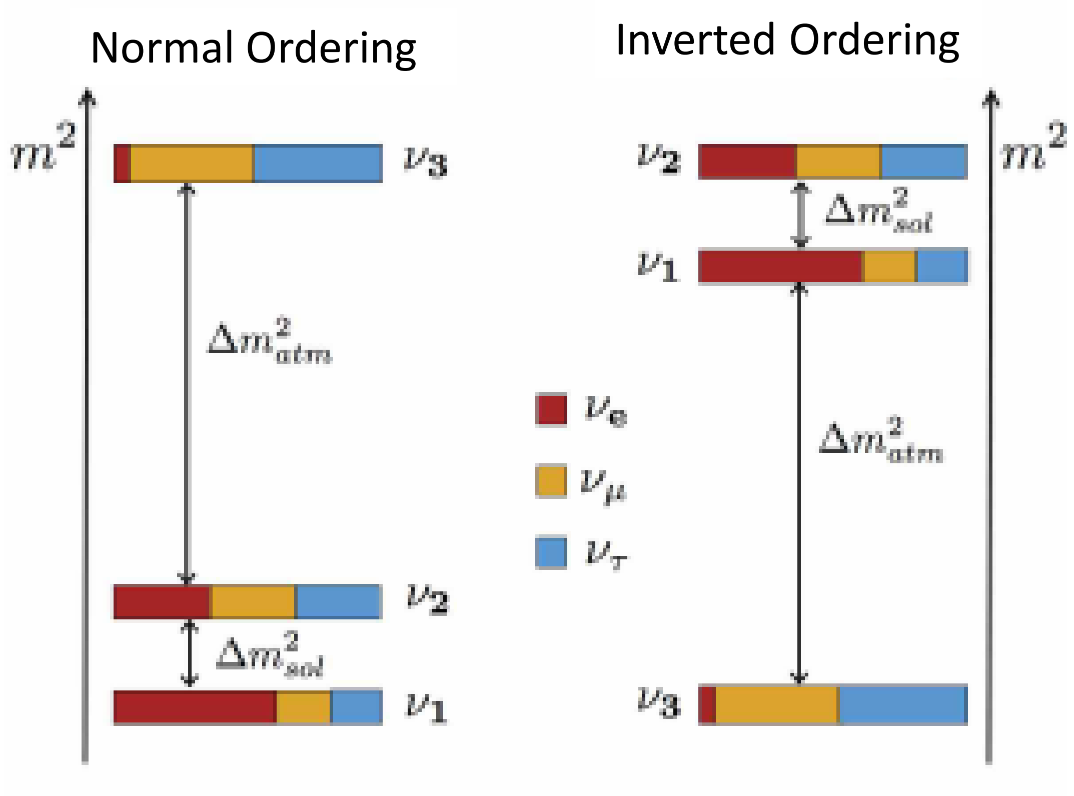
$$\begin{aligned} P_{\alpha\to\beta} = & \delta_{\alpha\beta} \\ & -4 \sum_{i>j} \mathfrak{R} \left(U^*_{\alpha i} U_{\beta j} U_{\alpha j} U^*_{\beta i}\right) \sin^2\left(1.27 \frac{\Delta m^2_{ij} L}{E}\right) \\ & +2 \sum_{i>j} \mathfrak{I} \left(U^*_{\alpha i} U_{\beta j} U_{\alpha j} U^*_{\beta i}\right) \sin\left(2.54 \frac{\Delta m^2_{ij} L}{E}\right). \end{aligned}$$



- Neutrino oscillation physics is only sensitive to the squared mass differences

Neutrino Mass Ordering (NMO)

- ❑ The absolute value of these mass differences has already been measured.
- ❑ The sign of Δm^2_{21} is fixed by Solar experiment.
- ❑ The sign of Δm^2_{32} is indeed not determined so far .
- ❑ NMO describes the ordering of these masses
  Only two possibilities remain: “Normal” or “Inverted”
- ❑ Many experiments aiming to measure NMO (JUNO …)



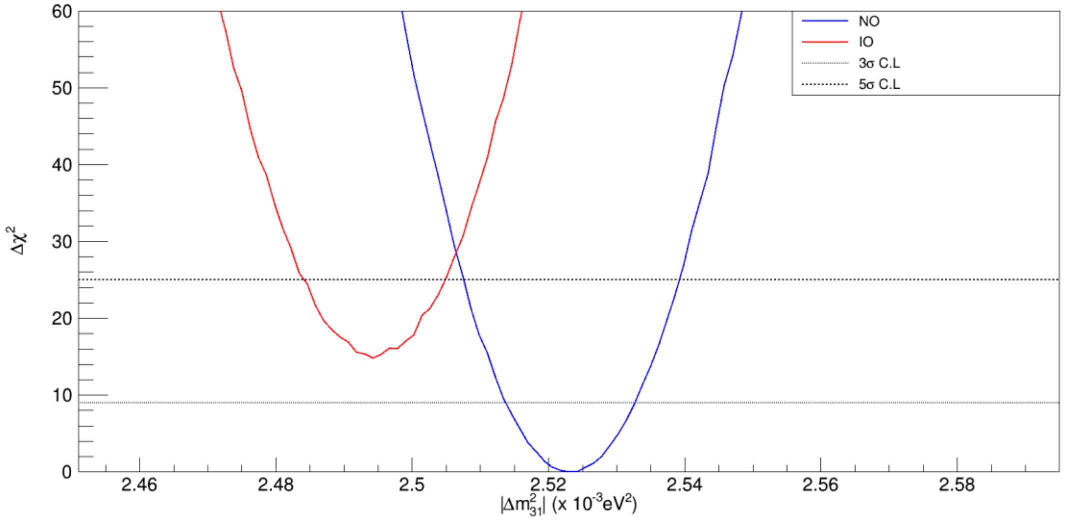
JUNO Experiment

JUNO is a “medium-baseline” (53km) reactor neutrino experiment located in China, under construction .

JUNO will be the largest Liquid Scintillator detector ever built (20kt) with energy resolution 3%.

Expected to measure the NMO with more than 3σ

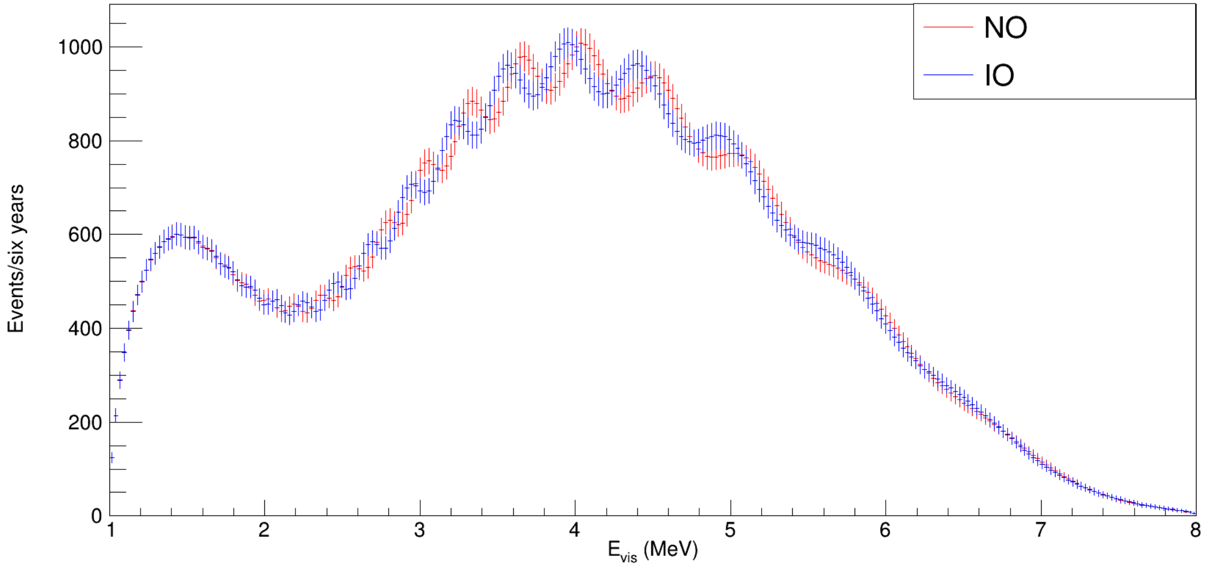
$$\Delta\chi^2_{\mathrm{MH}} = \chi^2_{\mathrm{IH}} - \chi^2_{\mathrm{NH}}$$



TIPP project

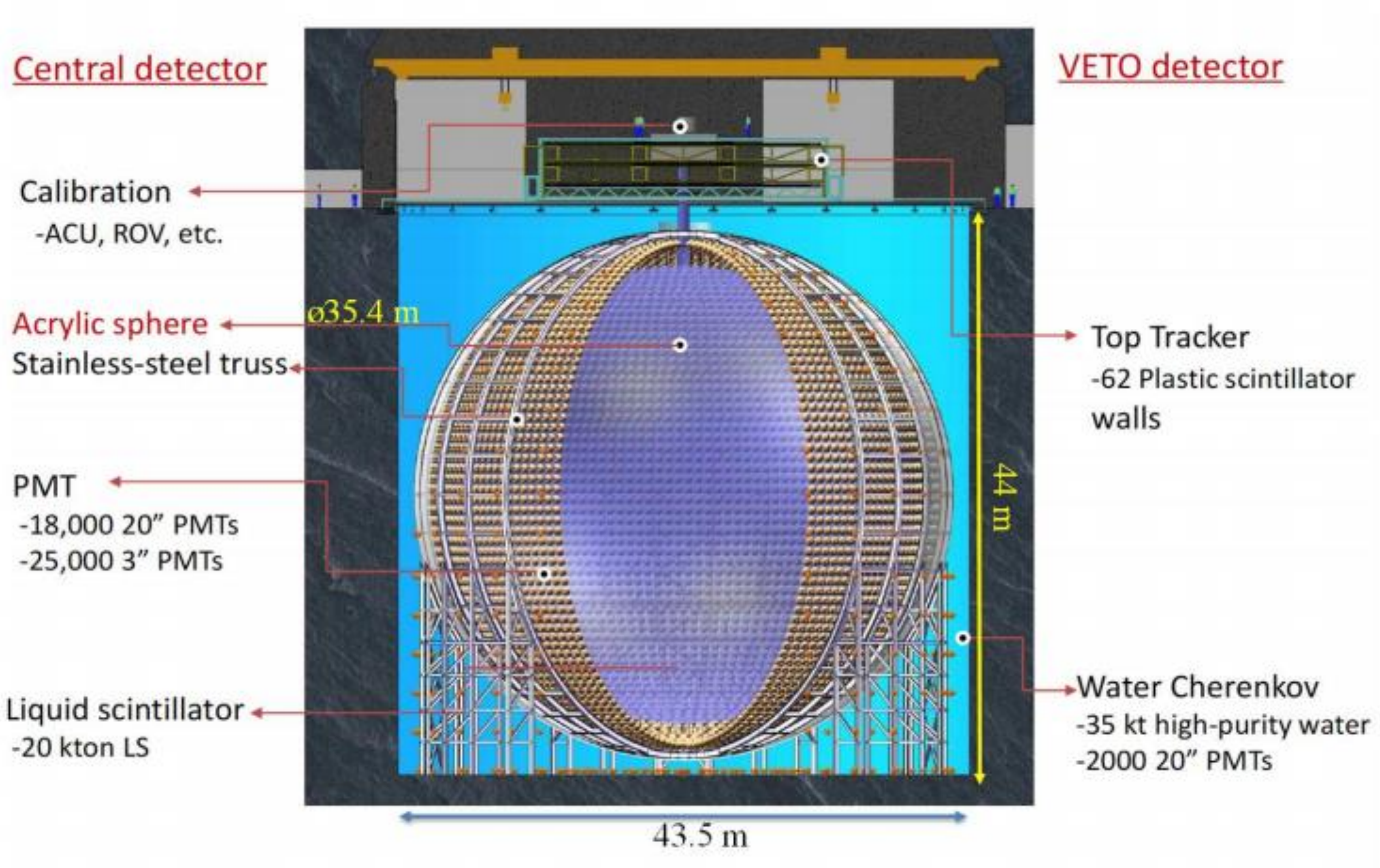
Δχ2=15 with No Systematics

Visible energy spectrum in the detector with 3% Energy Resolution.



TIPP project

JUNO Detector

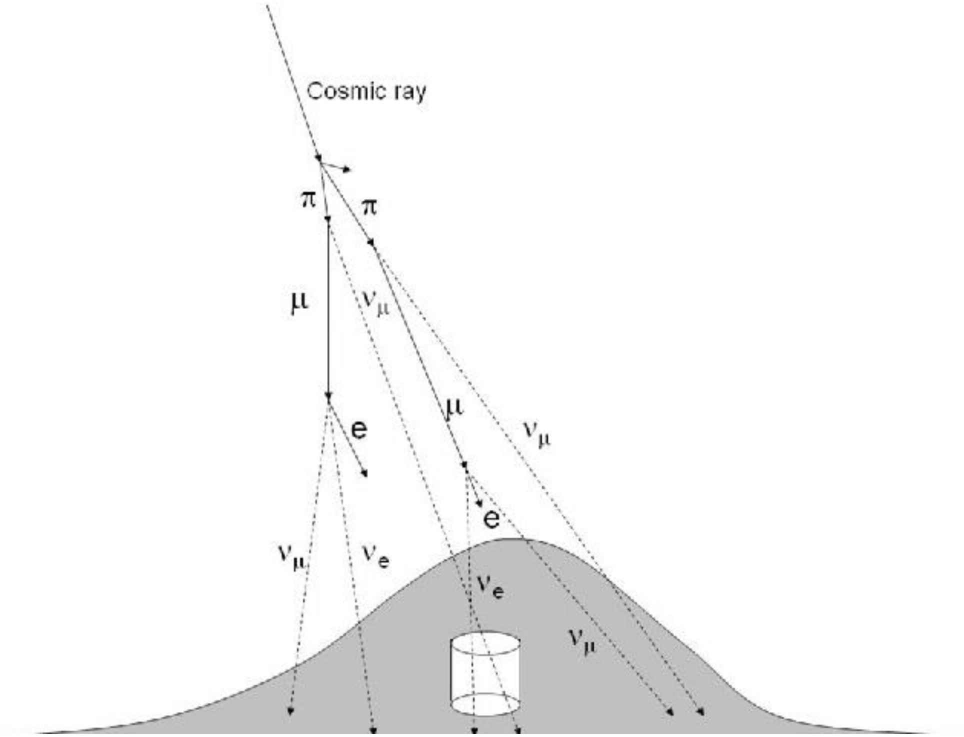


- The central detector is a liquid scintillator (LS) detector of 20 kT fiducial mass.
- JUNO has a Diameter of a 35.4 m
- The central detector is submerged in a water pool to be shielded from natural radioactivity from the surrounding rock and air.
- The water pool can be used to detect muons passing through the target volume .

Atmospheric Neutrinos…

- Interaction of the cosmic rays with the earth’s atmosphere
- $\nu e/\mu$ generated in atmosphere by meson decays
- At low energy, most common reaction chain is :

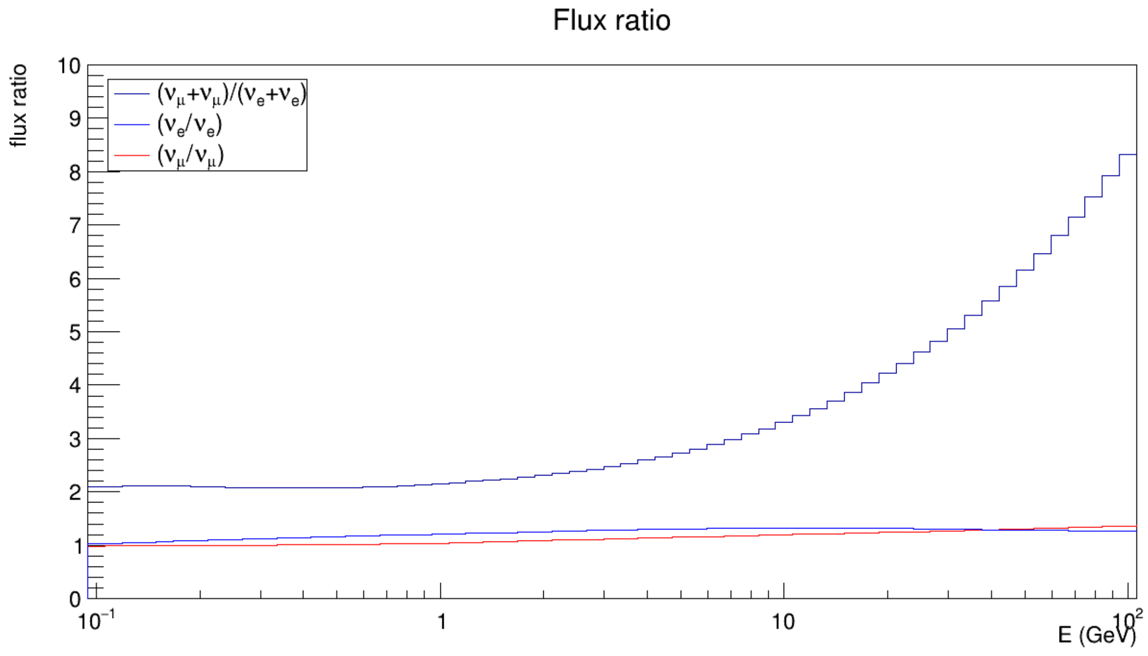
$$
\begin{aligned}
p^+ + N &\rightarrow \pi^\pm + X \\
\pi^+ &\rightarrow \mu^+ + \nu_\mu \\
\mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- &\rightarrow \mu^- + \bar{\nu}_\mu \\
\mu^- &\rightarrow e^- + \bar{\nu}_e + \nu_\mu .
\end{aligned}
$$

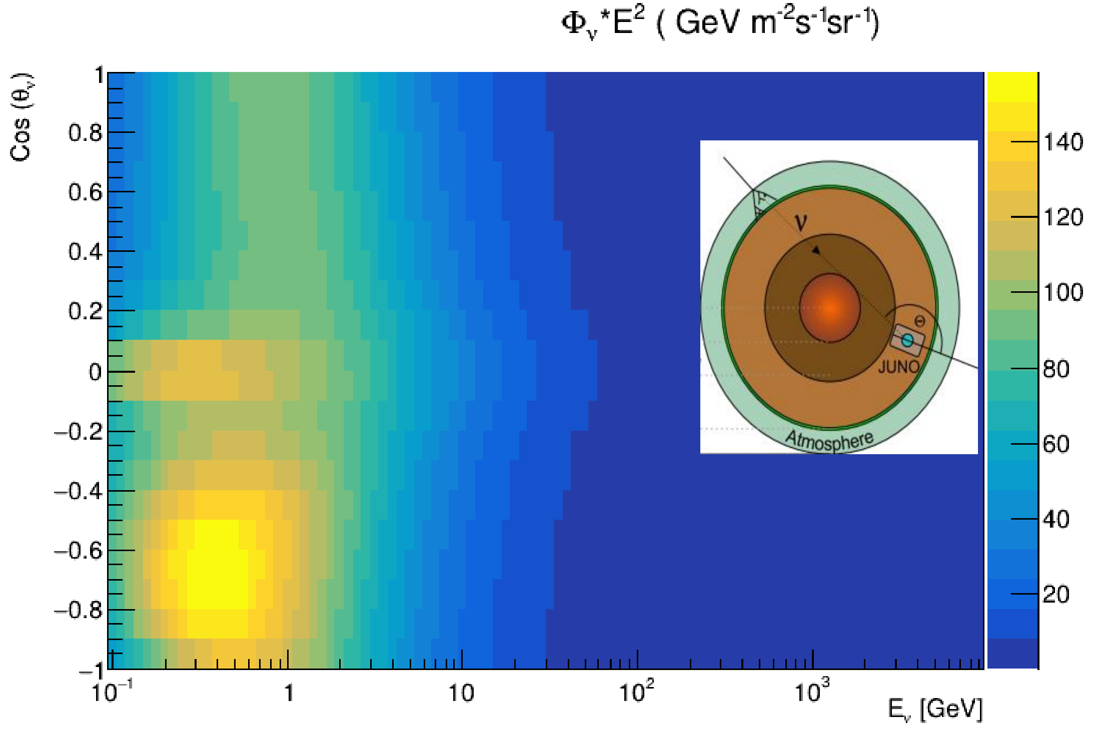


- the expected flux ratios is $\frac{\phi_{\nu\mu}+\phi_{\overline{\nu\mu}}}{\phi_{\nu e}+\phi_{\overline{\nu e}}} \geq 2$
- tau neutrinos are not generated in these decays

Initial Atmospheric Flux

Phys. Rev. D92, 023004 (2015) *M. Honda and al.*



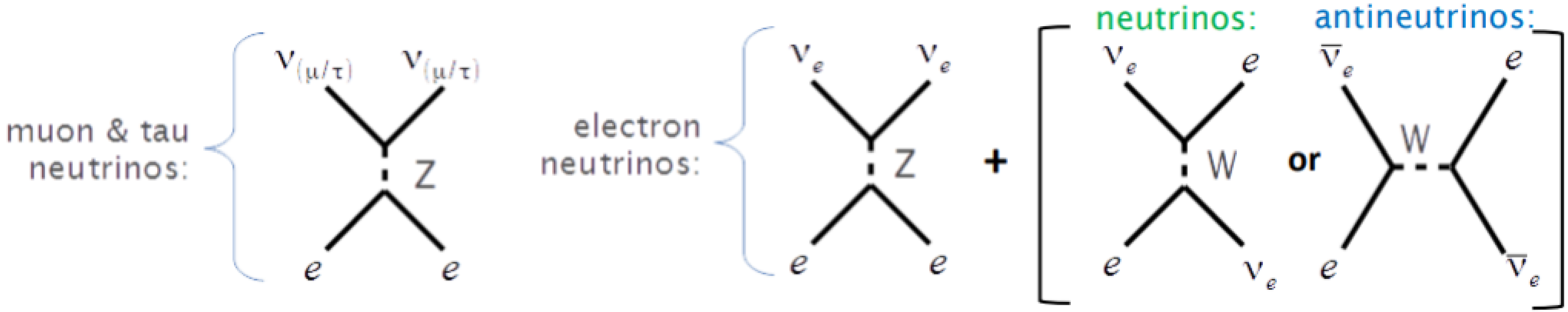


- At low energy the ratios is equal.
- These ratios increase at higher energies as muons are less likely to decay before hitting ground

- Atmospheric Neutrino in dependency of the Zenith angle and the energy .

Neutrino Oscillation…Matter Effects

- Interactions with electrons in the Earth (MSW-effects)



Schrodinger equation:

$$i\frac{d}{dt}\upsilon_f = (U\frac{M^2}{2E}U^T + V)\upsilon_f$$

$$With....M^2 = diag(m_1^2, m_2^2, m_3^2)$$

$$and\;...V = diag(2^{1/2}G_f N_e, 0, 0)$$

$$\sin(2\theta_M) = \frac{\sin(2\theta)}{\xi}$$

$$\Delta m_M^2 = \Delta m_{\text{atm}}^2 \cdot \xi$$

with:

$$\xi = \sqrt{\left(\sin^2(2\theta) + \left(\cos(2\theta) - \frac{A_{CC}}{\Delta m^2}\right)^2\right)}$$

$$A_{CC} = \pm 2\sqrt{2} \cdot G_F E_\nu N_e$$

+: neutrino
-: antineutrino

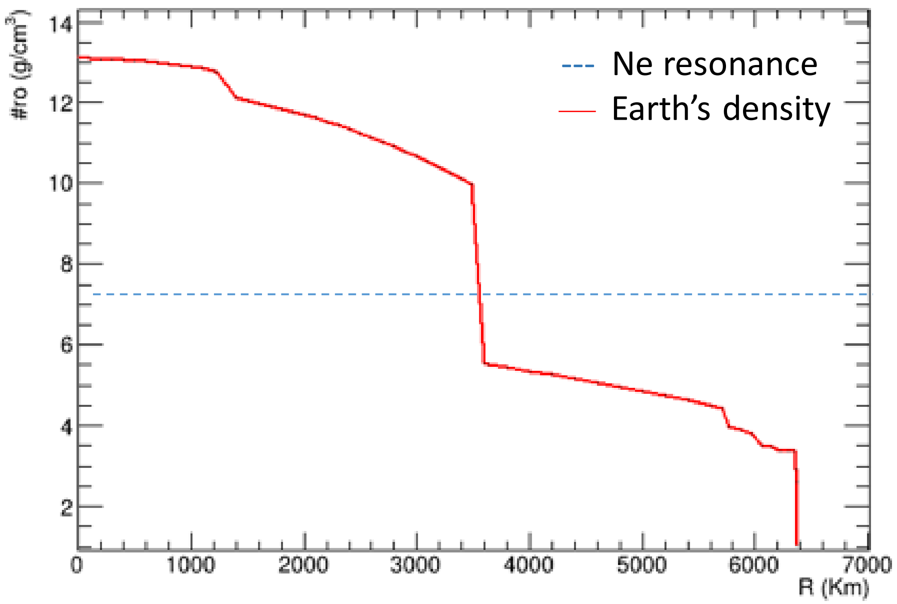
neutrino energy

electron density

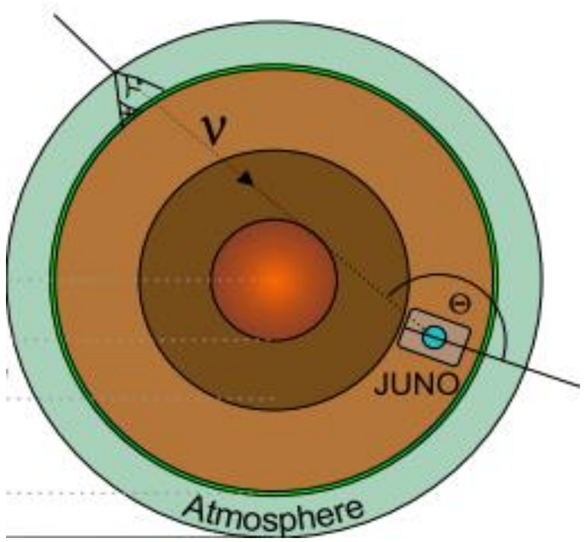
Resonance occurring from periodicity of matter profile

Neutrino Oscillation Inside the Earth

Electron Density Model :Preliminary Reference Earth Model (PREM)



PREM Model
10.17611/DP/9991844
A. M. Dziewonski & D. L. Anderson



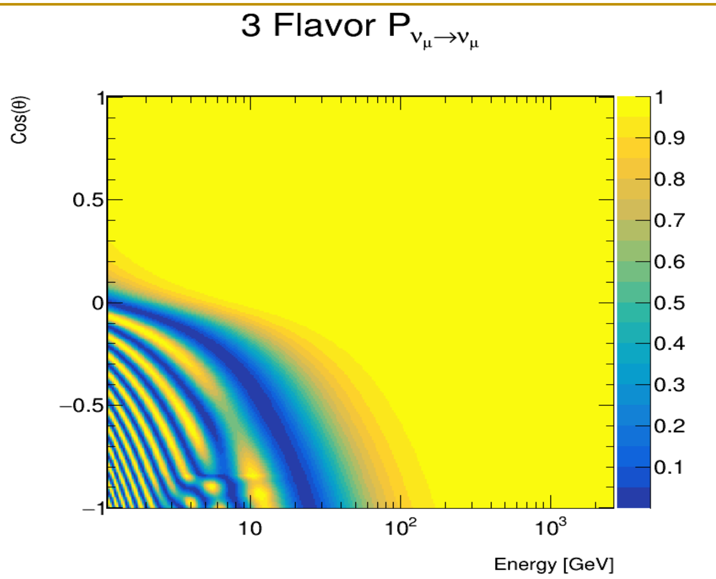
Using the **Best fit Parameter** From Global Fit :

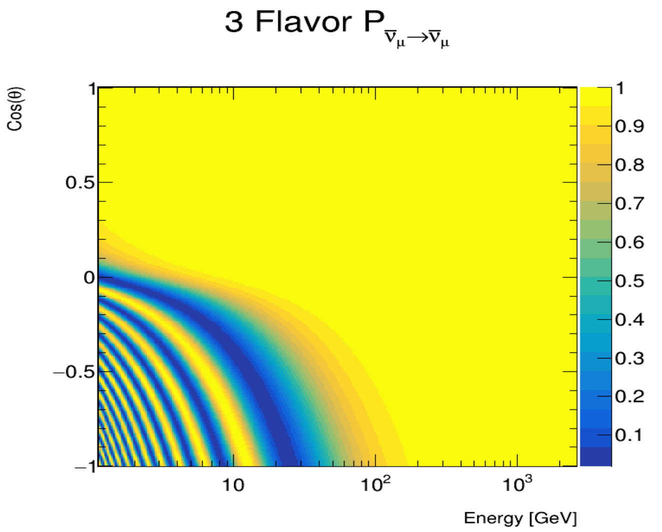
	Normal Ordering (best fit)	
	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.310^{+0.013}_{-0.012}$	$0.275 \to 0.350$
$\theta_{12}/^\circ$	$33.82^{+0.78}_{-0.76}$	$31.61 \to 36.27$
$\sin^2\theta_{23}$	$0.582^{+0.015}_{-0.019}$	$0.428 \to 0.624$
$\theta_{23}/^\circ$	$49.7^{+0.9}_{-1.1}$	$40.9 \to 52.2$
$\sin^2\theta_{13}$	$0.02240^{+0.00065}_{-0.00066}$	$0.02044 \to 0.02437$
$\theta_{13}/^\circ$	$8.61^{+0.12}_{-0.13}$	$8.22 \to 8.98$
$\delta_{CP}/^\circ$	217^{+40}_{-28}	$135 \to 366$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39^{+0.21}_{-0.20}$	$6.79 \to 8.01$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.525^{+0.033}_{-0.031}$	$+2.431 \to +2.622$

arXiv:1811.05487v1

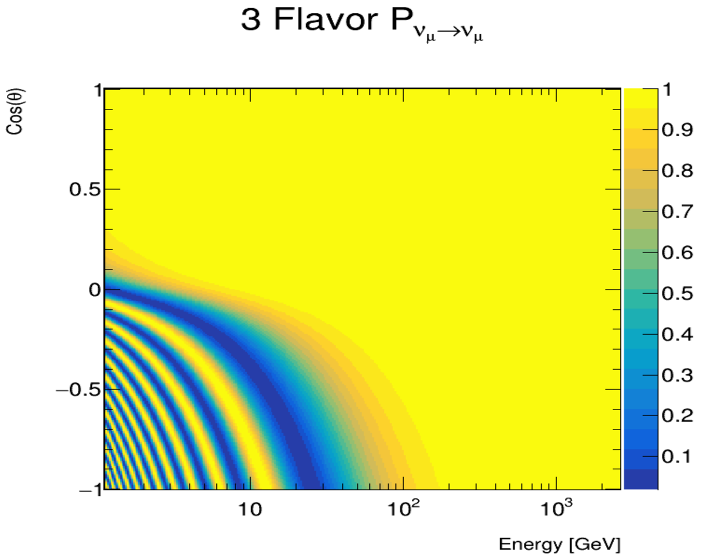
Neutrino Oscillation (NH and IH)

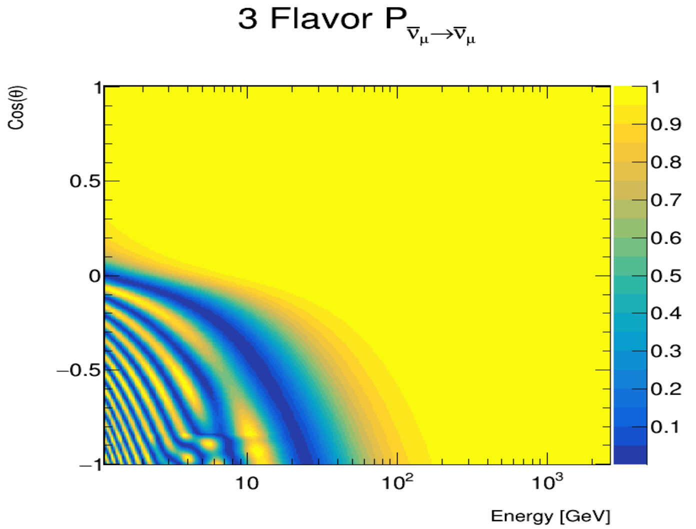
http://www.phy.duke.edu/~raw22/public/ Prob 3++





Normal Hierarchy





Inverted Hierarchy

→ **Vacuum Oscillation**: identical to ν and $\bar{\nu}$.

$$P_{IH}(\nu_\alpha \to \nu_\beta) = P_{NH}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

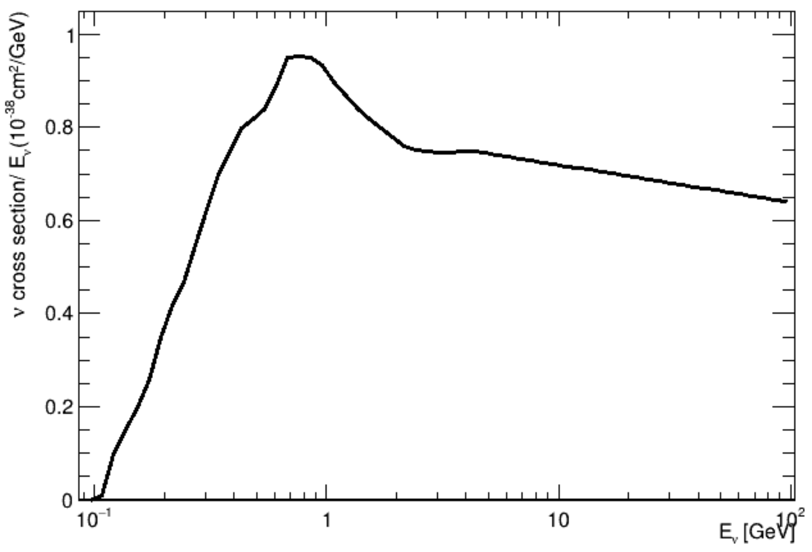
→ **Matter effects:** arise in ν for NO and $\bar{\nu}$ for IO

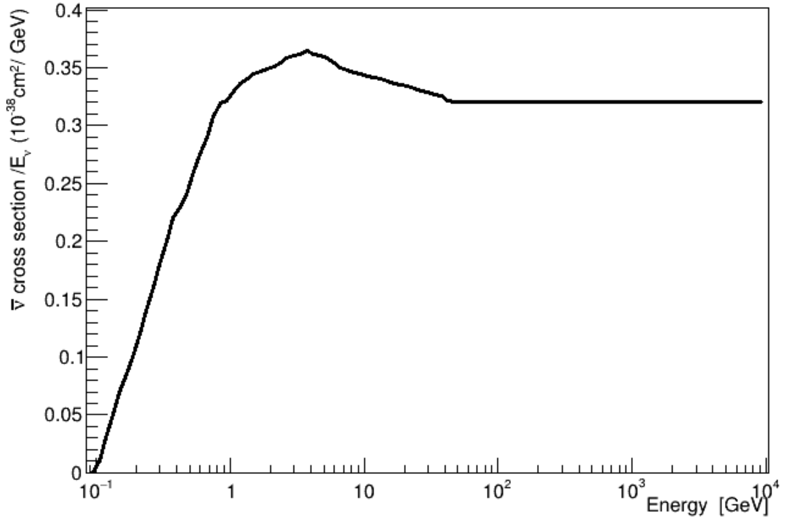
$$P_{NH}(\nu_\alpha \to \nu_\beta) = P_{IH}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

The Matter effects for neutrinos traveling through the dense Earth core appears for energy between 5 to 10 GeV and for cos(θ) ≤ −0.82

Neutrino Detection

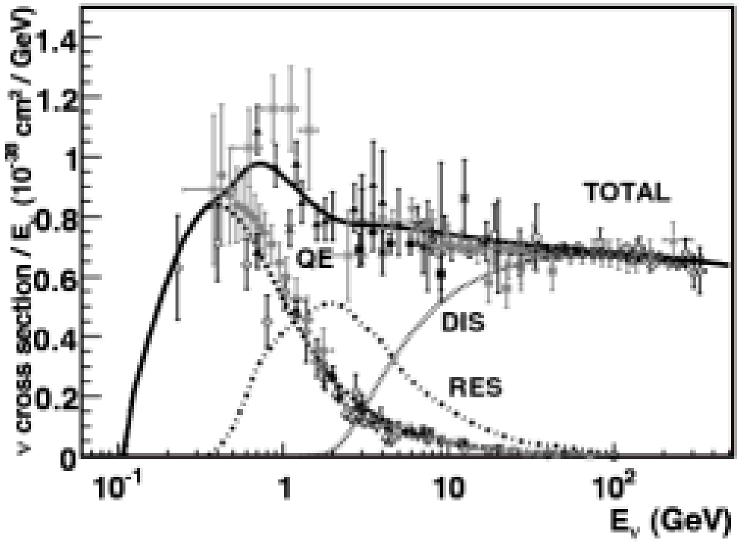
J. A. Formaggio and G. P. Zeller
arXiv:1305.7513v1

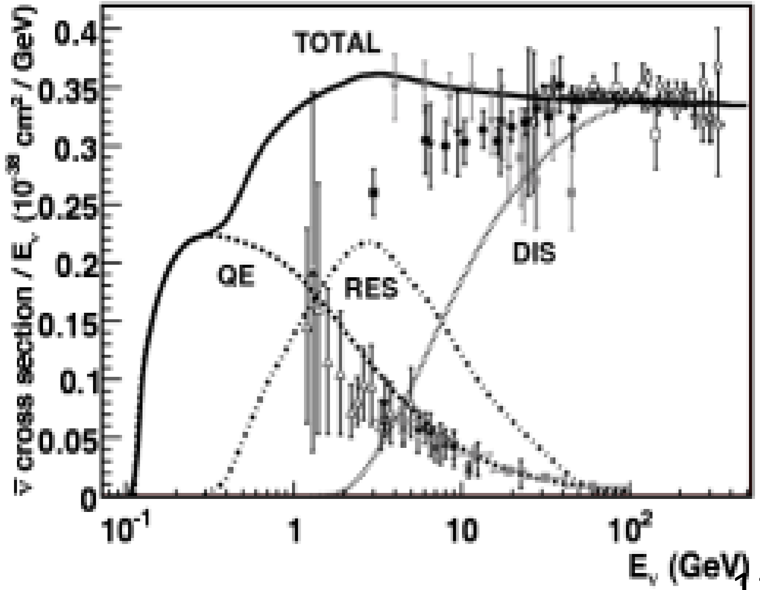




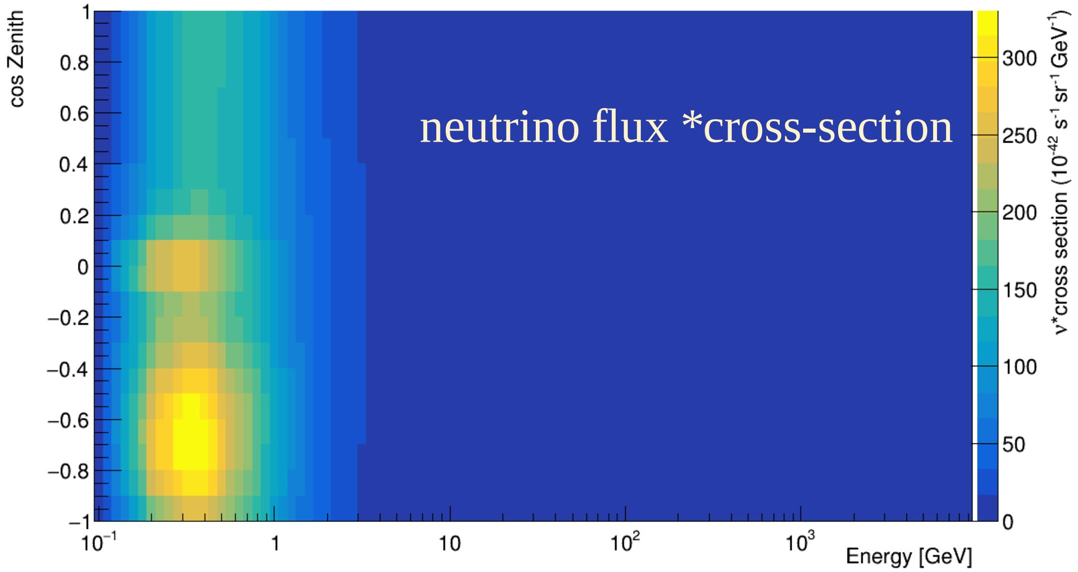
- Reproduce the total shape of cross section for Neutrino and Anti Neutrino

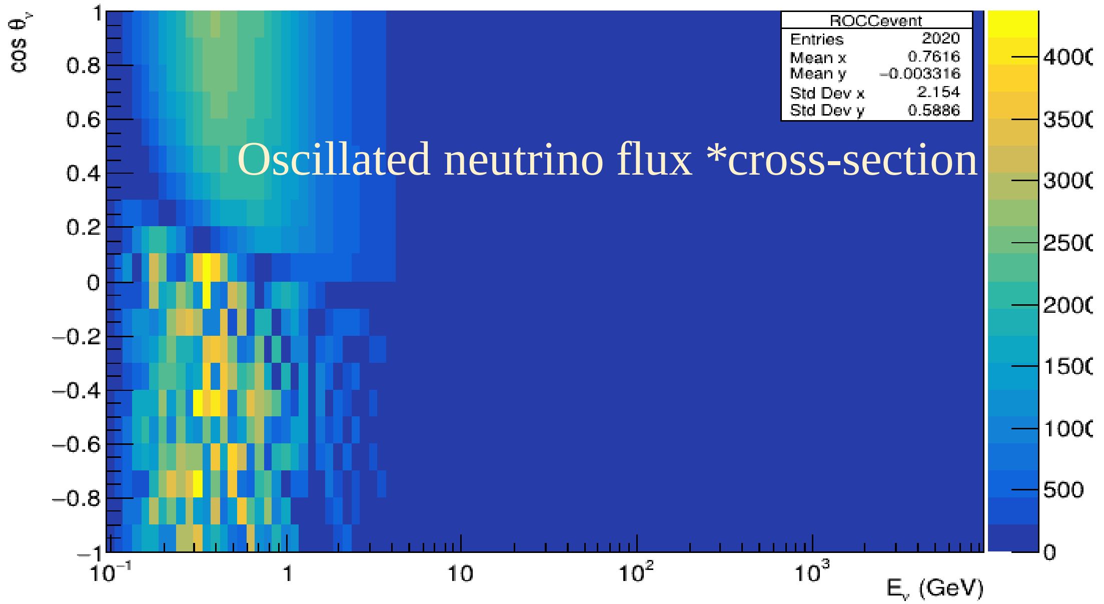
Global Study of the interaction through the detector





Realistic Atmospheric Neutrino Flux





$$F_\alpha(\cos\theta_Z, E_\upsilon) = \sum_{\iota=(e,\mu,\tau)} c_{\upsilon\iota}\phi_{\upsilon\iota}.P(\upsilon_\iota \to \upsilon_\alpha)$$

The expected number of events are calculated by using :

$$T_{ij,\upsilon\alpha} = 2\pi MT \int_{\cos\theta_Z^{i,\min}}^{\cos\theta_Z^{i,\max}} d\cos\theta_Z \int_{E_\upsilon^{j,\min}}^{E_\upsilon^{j,\max}} dE_\upsilon F_\alpha(\cos\theta_Z, E_\upsilon)\sigma_{\upsilon\alpha}$$

Where $\cos\theta_Z^{i,max/min}$ and $E_\nu^{i,max/min}$ are the borders of the bin i, j in zenith angle and energy (Honda Binning) .

	ν_μ - events	$\bar{\nu}_\mu$ - events	ν_e - events	$\bar{\nu}_e$ -- events
Rate Estimated by JUNO	8662	3136	6637	2221
Rate Calculated by me	8900	3242	7005	2105

Detector Performance

Selection Events and Classification

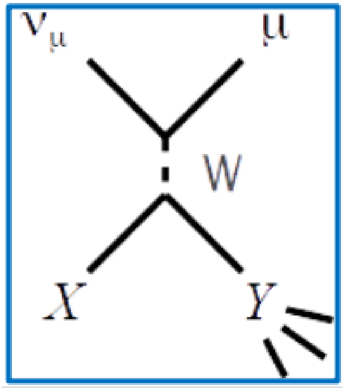
Two conditions to select events :

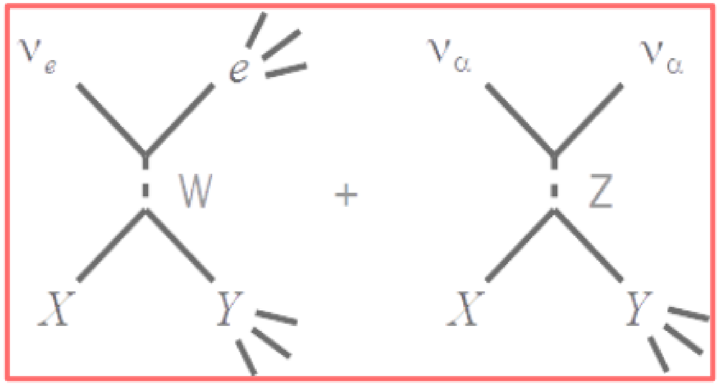
- Resolution for the charged Lepton direction
- Resolution for the charged flavor recognition

Selection :
Tracks with length Lμ ≥ 5 m

Classification :
Fully Contained (FC)

Energy Resolution σEvis = $0.01\sqrt{\text{Evis/GeV}}$
Angular Resolution better than 1°





- CC muon neutrinos

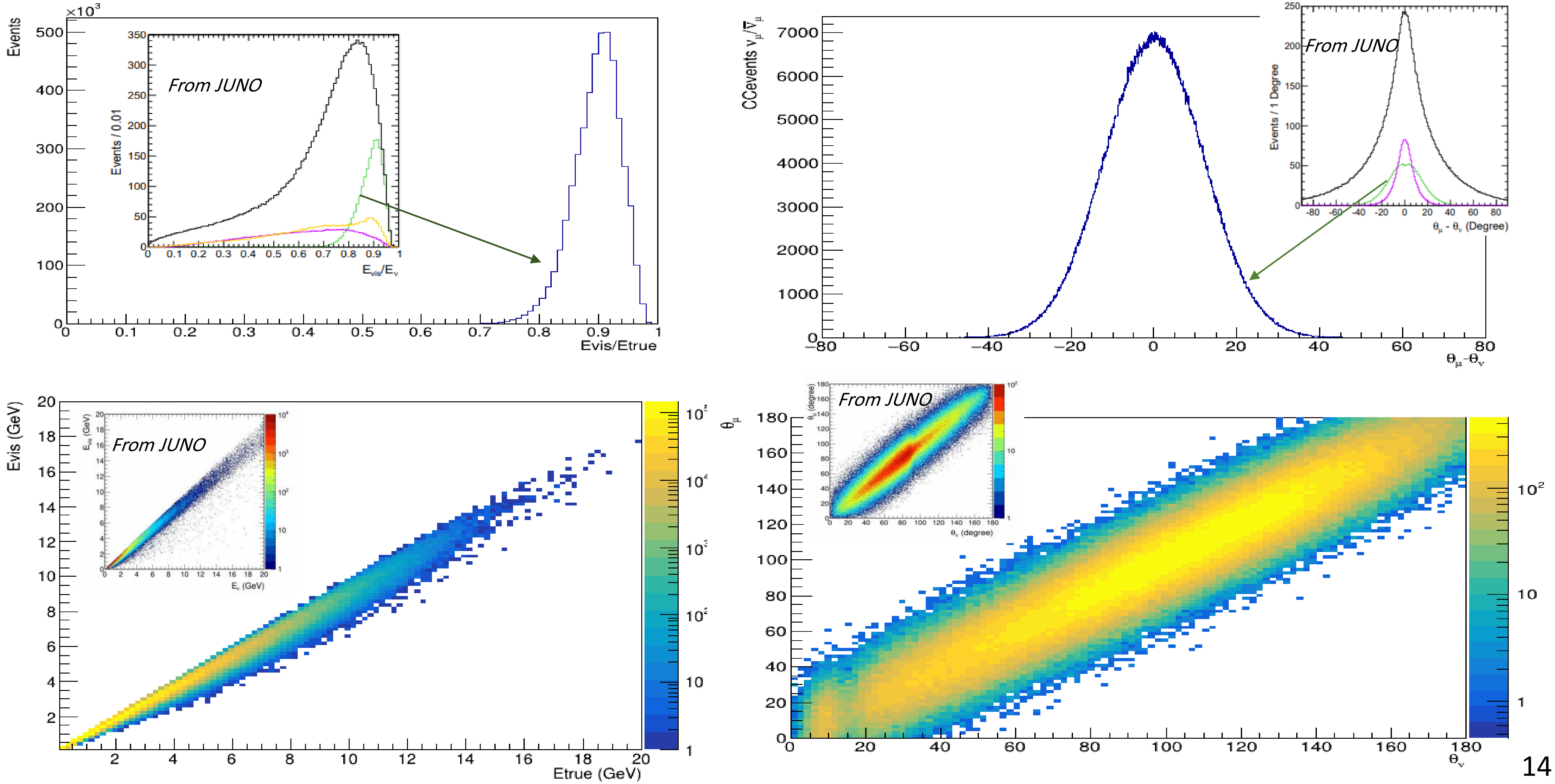
- CC Electron neutrinos
- NC interactions

- **The Selection efficiency of Lμ ≥ 5 m for 200 kton-years exposure:**

About 1K FC for a sample about of 12 k $\nu_\mu/\overline{\nu_\mu}$ CC events .

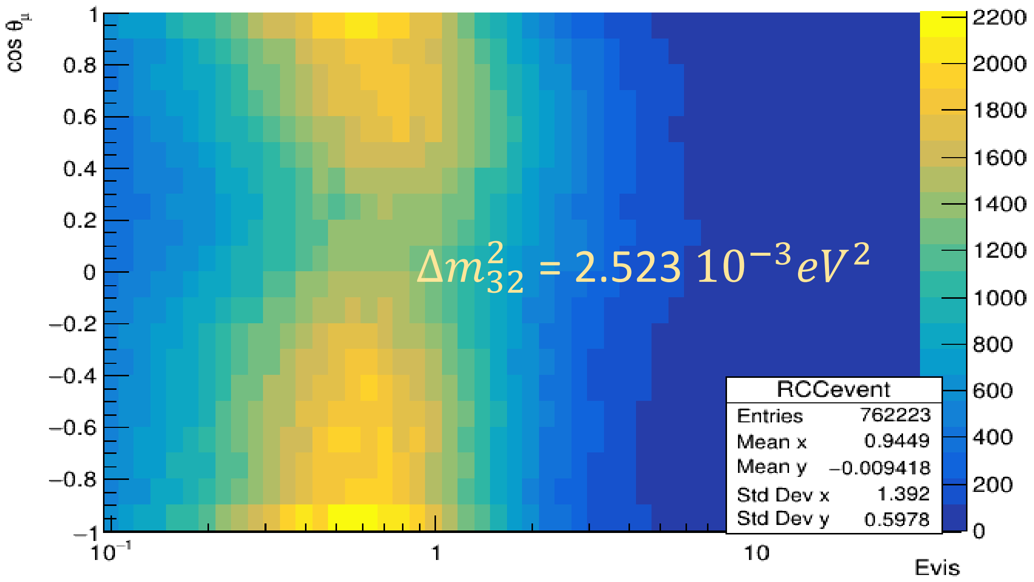
Parametrization of the Events Reconstruction

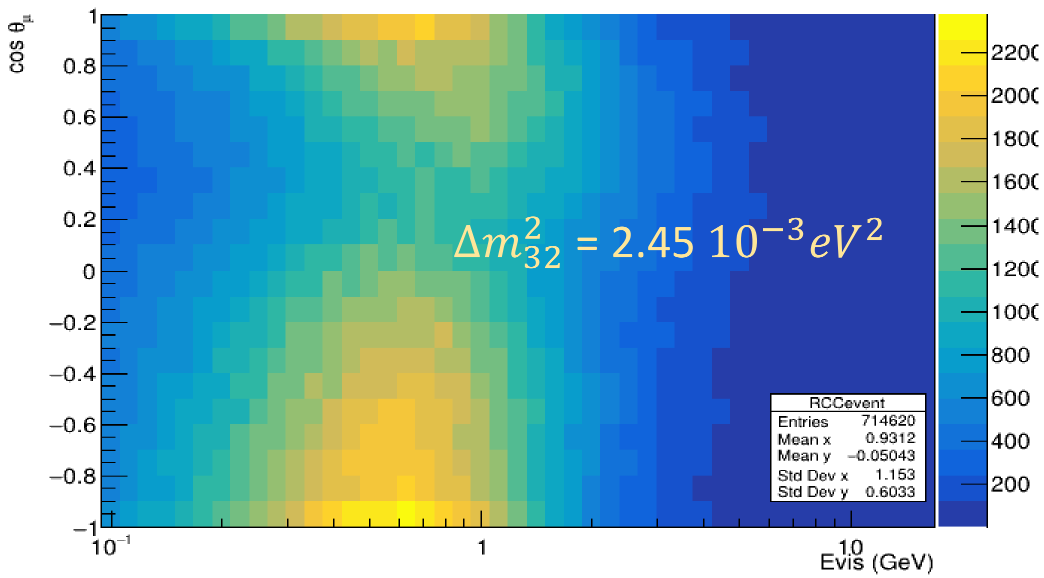
F. An et al. [JUNO Collaboration], J. Phys. G43(2016)3.



Estimated the Oscillated Atmospheric Neutrino

Under investigation





- There is a slight difference between them but not were we expect to have it

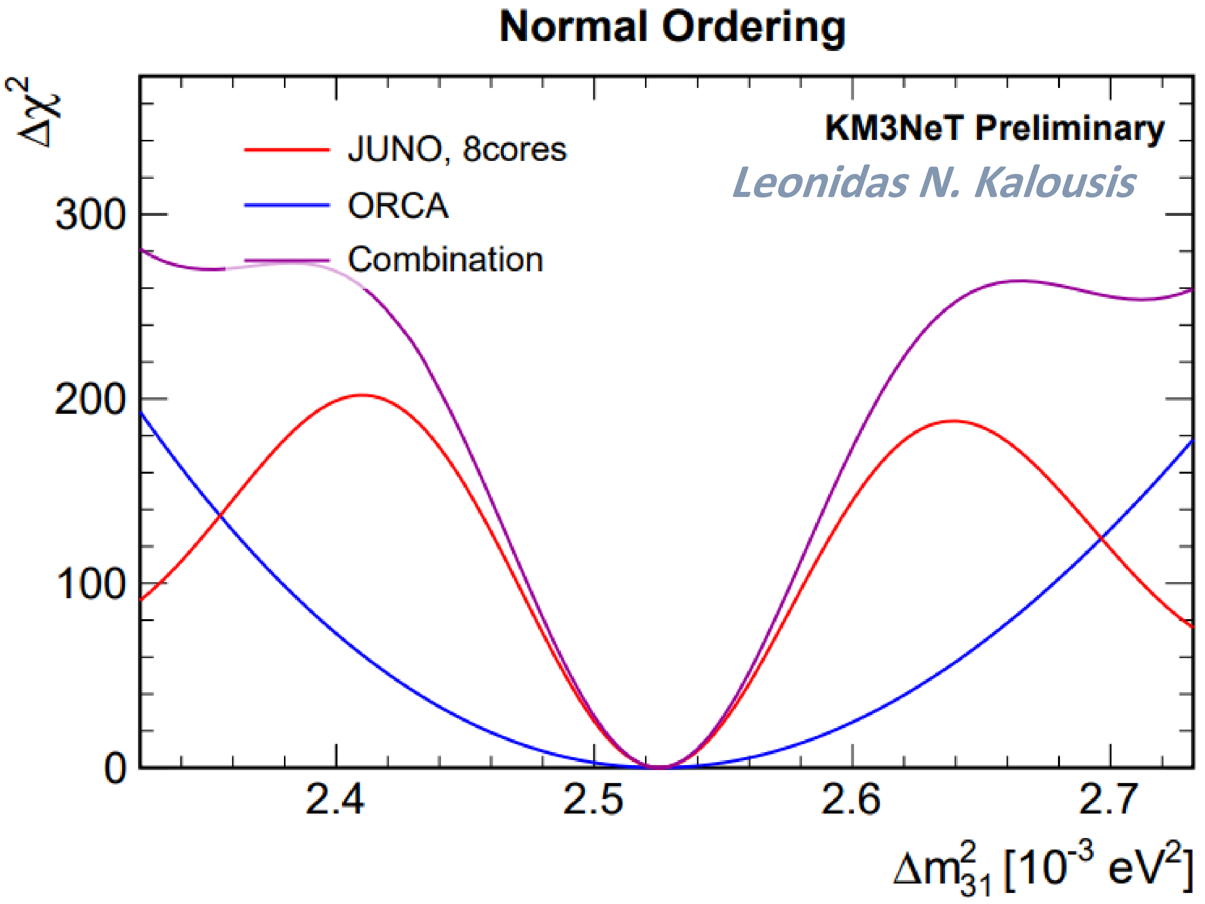
Next Step

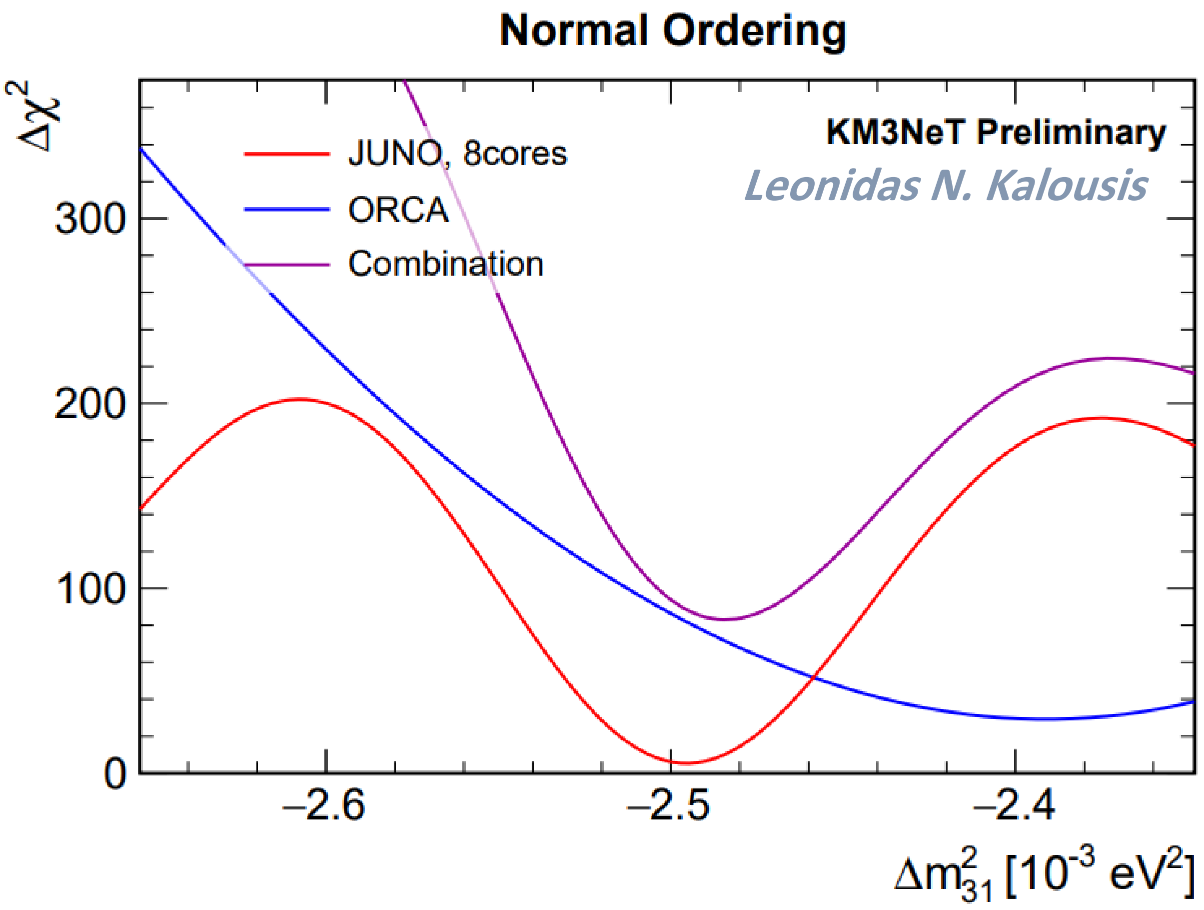
Statistical Approach

Estimate the sensitivity to Δm^2_{32} using χ^2 −method

Example of my last step Combination ORCA /JUNO

My work replace ORCA by JUNO Atmospheric





- **True Ordering** -> Minimal $\Delta\chi^2$ is found at the true value of Δm^2_{31}
- **Wrong Ordering** -> Δm^2_{31} are not the same for both experiments

- $\Delta\chi^2$ (JUNO)=9 -> 3σ
- $\Delta\chi^2$ (ORCA)=16 -> 4σ
- $\Delta\chi^2$ (JUNO+ ORCA)=80 ->9σ

Conclusion and Perspectives

❑Estimated Oscillated Neutrino Flux :

- ✓ Simulating the atmospheric neutrino flux following the HKKM2014 model.
- ✓ Digitize the cross section following Zeller and al.
- ✓ Simulating oscillation probabilities with Prob3++ and include them in the flux model.

❑Study the Detector Performance :

- ✓ Parametrize the events reconstructed in JUNO Yellow Book
- ➢ investigate the Oscillated Atmospheric Neutrino

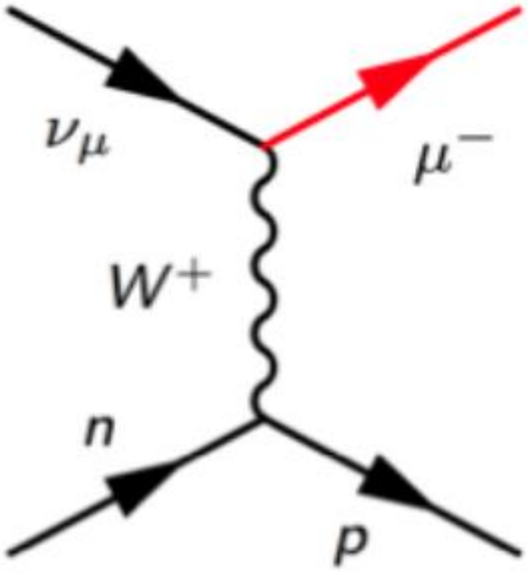
❑Next Step

- ➢ Study the sensitivity
- ➢ Using the Combination ORCA/JUNO's Strategy for a JUNO only Combination of reactor and Atmospheric

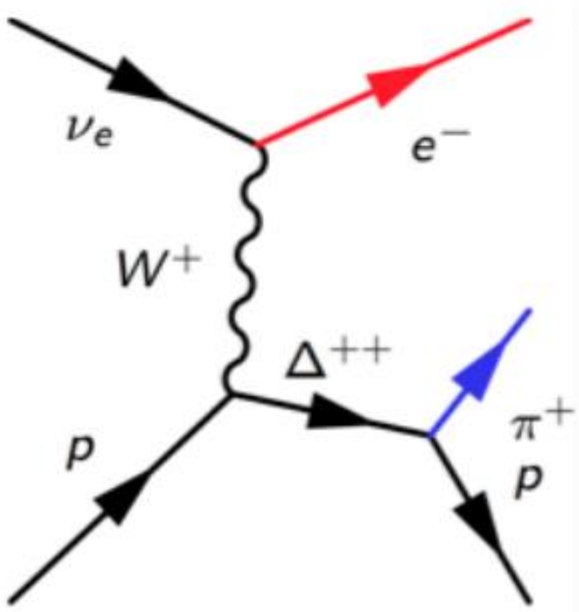
Back up

Neutrino Detection

- QE



Resonance



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